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High-performance InP/InGaAs heterojunction bipolar phototransistors for optoelectronic applications

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ABSTRACT

Phototransistors are attractive devices for applications in optical fiber telecommunication systems. They are used for the detection of optical signals and the amplification of these signals. This paper presents an investigation of how the technological parameters of indium phosphide (InP)/indium gallium arsenide (InGaAs) heterojunction bipolar phototransistor can impact its responsivity at two wavelengths, 1310 nm and 1550 nm. Based on the results of this investigation, we proposed optimized structures for the studied phototransistor. In this work, we used the software technology computer aided-design (TCAD)-Silvaco to simulate the physical and the electrical behavior of the different structures. The proposed optimized phototransistors can be used for various optoelectronic applications.

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1. INTRODUCTION

Semiconductor devices are indispensable for communication and information systems, they are more requests for various applications. III-V semiconductor materials are used in the fabrication of electronic devices owing to their transport properties. They have a direct band gap, and their electronic mobility is high. They have exceptional speed characteristics, furthermore they enable the operation of electronic devices at high frequencies [1].

Indium phosphide (InP) and indium gallium arsenide (InGaAs) are semiconductor materials of the III-V family of semiconductors. InP-InGaAs HBTs have proved to be excellent electronic devices, they are characterized by high electrical performances of speed and superior frequency [2], [3], and excellent current handling capability [4]. The heterojunction bipolar phototransistor (HPT) has almost the same epitaxial layer as the HBT, but the exclusive difference is in the electrode structure which allows illumination at the top of the device structure [5], [6]. The optical signal is absorbed in the base-collector region, and the signal is amplified by the intrinsic gain of the transistor [7], [8].

Different research works on HPT were performed for several decades [9]–[11]. HPTs are considered promising alternatives to devices such as metal-semiconductor-metal (MSM), the PIN and avalanche photodiodes [12], [13]. Furthermore, HPTs are more advantageous for highly sensitive infrared photodetection and imaging over the PIN and the avalanche photodiode (APD) due to their excellent characteristics of high gains without differences in high potentials and without excess noise [14]–[16]. In addition, the operation of HPTs can be done at a low bias voltage, and with a low gain sensitivity to the bias voltages [17]. There are

several applications where photodetectors based on InP are requested and used, such as biomedical field, optical communication systems, environment and also firms of chemistry for near infrared (NIR) light detection [18].

The objective of this work is to investigate the impact of technological parameters on the electrical performances of the InP/InGaAs HPT in terms of the responsivity at the wavelengths 1310 nm and 1550 nm. This investigation will help us to propose some optimized devices with different values of responsivities. These devices can be used in various optoelectronic applications.

2. INDIUM PHOSPHIDE/INDIUM GALLIUM ARSENIDE HPT MODELLING

In this work, we designed the InP/InGaAs HPT, which is mainly based on the HBT structure studied in papers [2], [19]–[21]. It is basically composed of two III-V semiconductor materials made from two alloys, a binary alloy for InP, and InGaAs. The topology of HBT structure has been adapted to receive light. Regarding the modifications made in HBT structure, a base contact has been removed, and the emitter contact has been reduced. The type of illumination is from above.

As detailed in Table 1 and shown in Figure 1, the epitaxial layer structure of the InP/InGaAs HPT comprises a cap layer, an emitter 1 layer, an emitter 2 layer, a spacer layer, a base layer, a collector layer, a sub-collector layer and a buffer layer. For the fabrication of this device, there are different techniques used for the growth of epitaxial layers such as metal organic chemical vapor deposition (MOCVD), and molecular jet epitaxy (MBE) technique [22].

Figure 1 shows the device structure of the InP/InGaAs HPT that respects the order of the epitaxial layers of the Table 1. It is an NPN heterojunction bipolar phototransistor; the ohmic contacts are made of the material gold. In the top view, the optical window as illustrated is the space between the base and the emitter. The illuminated surface is equal to 4×4 μm^2. The illumination is considered vertical to the HPT optical window. To design the device structure, we have carefully layered and meshed the InP/InGaAs HPT using the device editor DevEdit which allows the creation of the device structure.

Table 1. Layer structure for lattice-matched InP/$In_{0.47}Ga_{0.53}$ HPT

Layer	Material	Doping (cm^{-3})	Thickness (nm)
Cap	$In_{0.47}Ga_{0.53}As$	$n=1\times10^{19}$	135
Emitter 1	$In_{0.47}Ga_{0.53}As$	$n=1\times10^{17}$	135
Emitter 2	InP	$n=1\times10^{17}$	40
Spacer	$In_{0.47}Ga_{0.53}As$	-	5
Base	$In_{0.47}Ga_{0.53}As$	$p=1.5\times10^{19}$	65
Collector	$In_{0.47}Ga_{0.53}As$	$n=1\times10^{16}$	630
Sub-collector	$In_{0.47}Ga_{0.53}As$	$n=1\times10^{19}$	500
Buffer	$In_{0.47}Ga_{0.53}As$	-	10
Substrate		Semi-insulating InP	

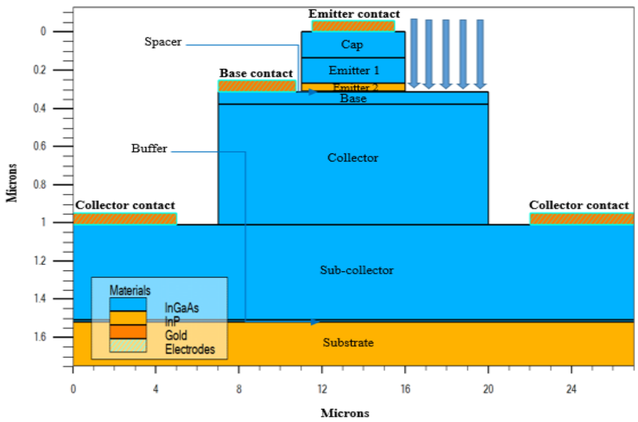

Figure 1. Schematic device structure of the InP/$In_{0.47}Ga_{0.53}$ HPT

2.1. Physical and numerical modelling of InP/InGaAs HPT

ATLAS is a device simulator. It helps users predict the electrical behavior of any electronic device. It has been integrated into the simulation program for the physical and numerical modelling of HPT.

2.1.1. Physical modelling

The physical modelling of electronic devices allows to take into consideration the physical phenomena and mechanisms occurring within these devices. After designing the HPT device structure, we added in the simulation some physical models integrated into the simulator. Among these physical models, we cite the carrier statistical model (BGN), the recombination model (SRH), the Selberherr's model of the impact of ionization (IMPACT SELB), the band-to-band model (BBT.STD), the optical recombination model (OPTR), the parallel electric field dependence model (FLDMOB), and the fermi-dirac model (FERMI).

2.1.2. Numerical modelling

Semiconductor equations were solved employing the newton method. Among these equations, the carrier continuity equations, the Poisson's equation, the drift and the diffusion equations for both the electrons and the holes. These equations allow calculating currents, potentials and charge carriers, more details can be found elsewhere [21].

3. RESULTS AND DISCUSSION

This study is carried out at room temperature T=300 K, for the two wavelengths 1310 nm and 1550 nm. The photodiode mode is taken for at V_{ce}=0 V and V_{be}=0 V. The phototransistor mode is considered for the bias conditions at V_{ce}=1.6 V and V_{be}=0.86 V.

3.1. HPT responsivity

3.1.1. Responsivity definition

The responsivity *R (λ)* is defined as the ratio of photo-generated current to the input optical power and is expressed as (1) [5], [23]:

$$R\ (\lambda) = \frac{\lambda I_C(\lambda)}{hc\Phi_0(1-R_f)} \qquad (1)$$

where h is planks constant, c is the velocity of light, Φ_0 is total incident flux density and R_f is the Fresnel reflection coefficient. The flux-dependent collector current (I_C) is the sum of individual current contributions in the base, sub-collector and B-C depletion regions [23].

The phototransistor is working in two modes, photodiode mode and phototransistor mode; we are more interested in the phototransistor mode. The figures below present the simulation results of the studied InP/InGaAs HPT. We simulated the collector current as a function of light intensity, after that we extracted the responsivity in phototransistor mode R_{HPT}. For the applied light intensity, it is from 0 to 100 W/cm^2. All the results for responsivity are taken for the phototransistor mode, more precisely for V_{ce}=1.6 V and V_{be}=0.86 V. We investigated the impact of technological parameters on the responsivity of the studied HPT.

3.1.2. Responsivity of the studied HPT at λ=1310 nm and λ=1550 nm

Figure 2 and Figure 3 present the evolution of the collector current (A) as a function of the light intensity (W/cm^2) respectively at λ=1310 nm and λ=1550 nm. The light intensity is from 0 to 100 W/cm^2. It is clearly noticed a linear evolution, the collector current increases gradually with the increase of the applied light intensity. The responsivity R_{HPT} is approximately equal to 3.2 A/W at λ=1310 nm, and it is around 2.7 A/W at λ=1550 nm.

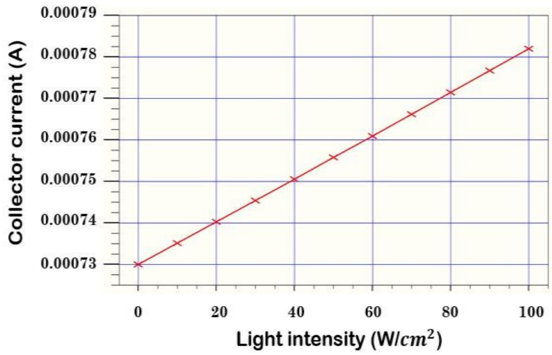

Figure 2. Collector current as a function of light intensity at λ=1310 nm and V_{ce}=1.6 V

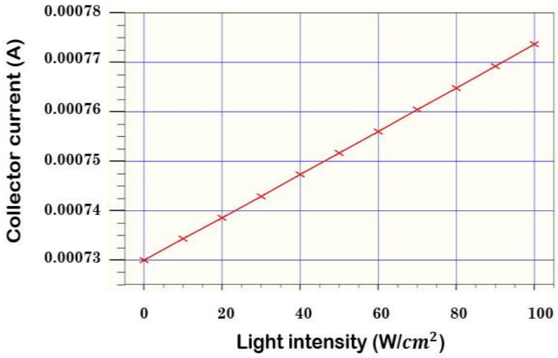

Figure 3. Collector current as a function of light intensity at λ=1550 nm and V_{ce}=1.6 V

We have investigated the impact of technological parameters of the studied phototransistor on its responsivity in the phototransistor mode. This investigation was performed at room temperature T=300 K respectively for the wavelength λ=1310 nm and λ=1550 nm. The evaluated technological parameters are the base width, the base doping, and the collector doping.

A. Impact of technological parameters on responsivity in phototransistor mode at λ=1310 nm

1) Impact of base width

Based on Figure 4, the collector current (A) increases with the application of light intensity (W/cm^2). We noticed that the collector current increases with the reduction of the base width W_b. Figure 5 shows the responsivity R_{HPT}(A/W) of the HPT that varies according to the base width W_b for the wavelength λ=1310 nm. We observed that the responsivity had an increasing trend with the decrease in the base width. Therefore, the decreased values of base width allowed obtaining high values of the responsivity of the HPT, the intrinsic current gain of a transistor increases when we reduce the base width [20]. The base width has the same important impact for the intrinsic current gain and the responsivity.

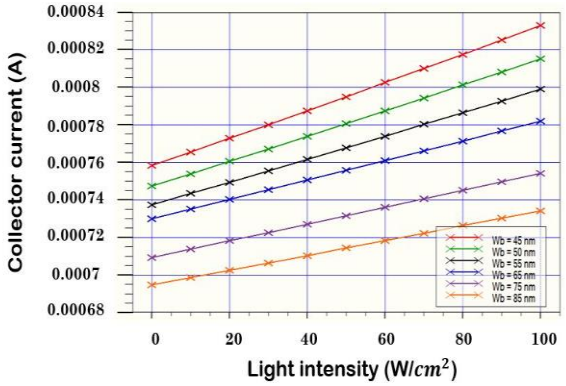

Figure 4. Collector current as a function of light intensity for different base width W_b at λ=1310 nm and V_{ce}=1.6 V

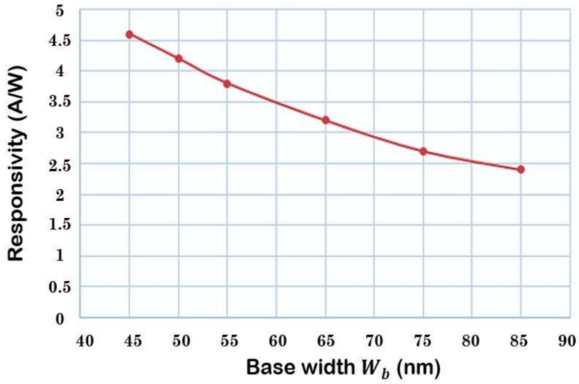

Figure 5. Responsivity as a function of base width W_b at λ=1310 nm and V_{ce}=1.6 V

2) Impact of base doping

Figure 6 presents the evolution of the collector current (A) as a function of the light intensity (W/cm^2) for different base doping N_b at λ=1310 nm. According to Figure 7, we find that when the base doping N_b is reduced, the responsivity R_{HPT}(A/W) increases gradually and reaches a large value for N_b = 1x$10^{18}cm^{-3}$. The base doping N_b has a significant impact on the responsivity of the studied phototransistor.

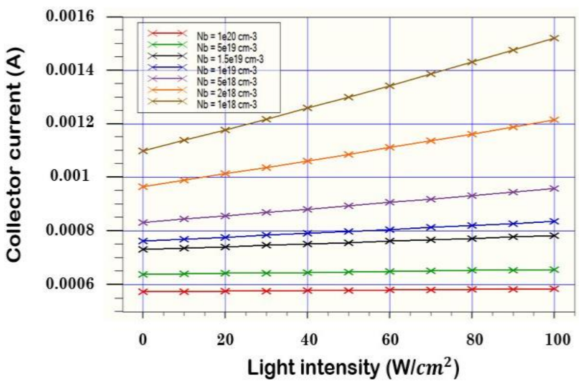

Figure 6. Collector current as a function of light intensity for different base doping N_b at λ=1310 nm and V_{ce}=1.6 V

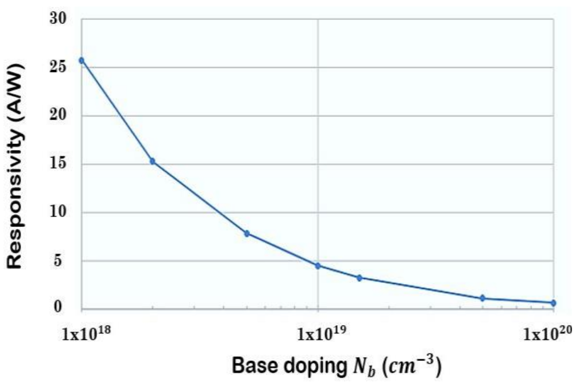

Figure 7. Responsivity as a function of base doping N_b at λ=1310 nm and V_{ce}=1.6 V

3) Impact of collector doping

According to Figure 8, the collector current I_C increases with the increasing of applied light intensity (W/cm^2) at λ=1310 nm. The investigated values of collector doping are between $1\times10^{14}\ cm^{-3}$ and $1\times10^{17}\ cm^{-3}$. Based on Figure 9, we noticed from the examined values that the responsivity R_{HPT}(A/W) increases slowly and its value is constant for some values of N_c. Collector doping has a small impact on HPT responsivity compared to other technological parameters.

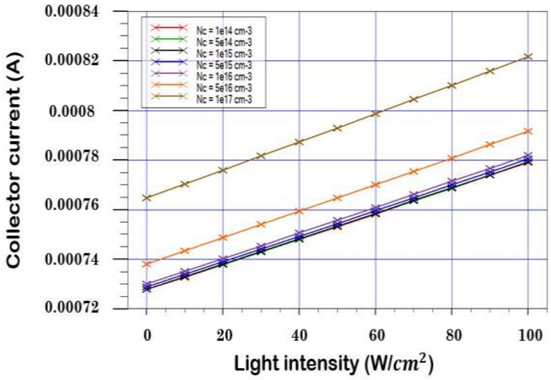

Figure 8. Collector current as a function of light intensity for different collector doping N_c at λ=1310 nm and V_{ce}=1.6 V

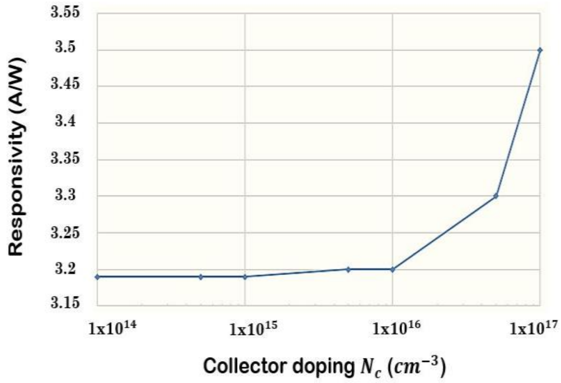

Figure 9. Responsivity as a function of collector doping N_c at λ=1310 nm and V_{ce}=1.6 V

B. Impact of technological parameters on responsivity in phototransistor mode at λ=1550 nm

1) Impact of base width

Figure 10 presents the curve of collector current I_C as a function of the light intensity for different values of base width W_b between 45 nm and 85 nm. According to Figure 11, it is observed that the responsivity R_{HPT}(A/W) decreases with the increasing of the base width W_b at the wavelength 1550 nm. The base width as a technological parameter has an impact on the responsivity of this studied photodetector.

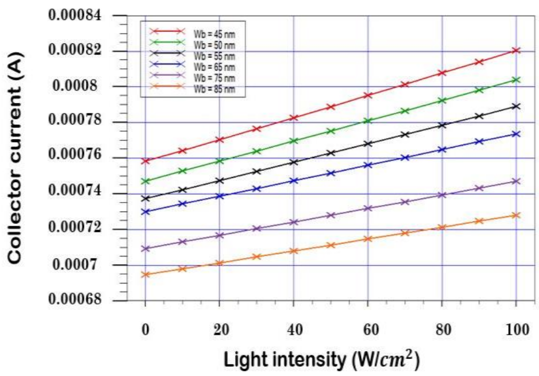

Figure 10. Collector current as a function of light intensity for different base width W_b at λ=1550 nm and V_{ce}=1.6 V

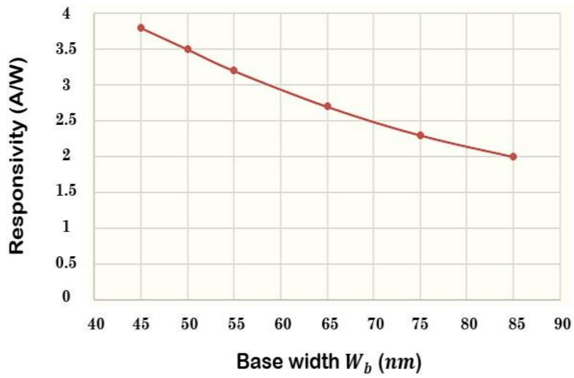

Figure 11. Responsivity as a function of base width W_b at λ=1550 nm and V_{ce}=1.6 V

2) Impact of base doping

Figure 12 presents the evolution of the collector current as a function of the light intensity (W/cm^2) for different base dopings N_b at λ=1550 nm. Based on Figure 13, we find that the responsivity R_{HPT}(A/W) increases when the base doping N_b is reduced. The base doping N_b corresponding to $1\times10^{18}\ cm^{-3}$ gives the highest responsivity among the investigated base dopings ranging from $1\times10^{18}\ cm^{-3}$ up to $1\times10^{20}\ cm^{-3}$. Therefore, the base doping N_b has a considerable impact on the responsivity of the phototransistor.

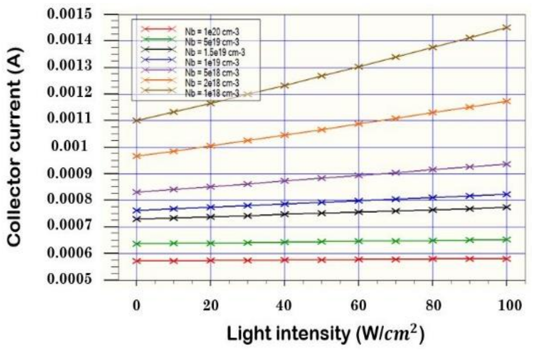

Figure 12. Collector current as a function of light intensity for different base doping N_b at λ=1550 nm and V_{ce}=1.6 V

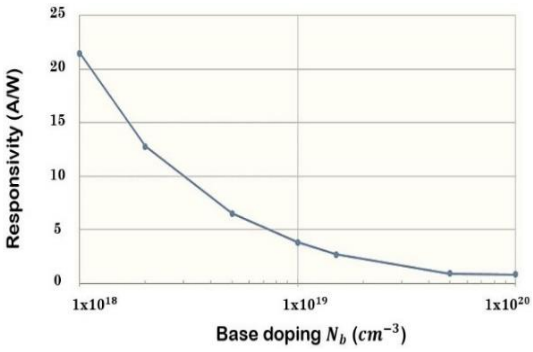

Figure 13. Responsivity as a function of base doping N_b at λ=1550 nm and V_{ce}=1.6 V

3) Impact of collector doping

According to Figure 14, the collector current I_C increases with the increasing of the applied light intensity (W/cm^2) at λ=1550 nm. The investigated values of collector doping range from 1×10^{14} cm^{-3} to 1×10^{17} cm^{-3}. Based on Figure 15, we noticed that responsivity R_{HPT} as a function of collector doping N_c varies in a very light way. The responsivity increases slightly.

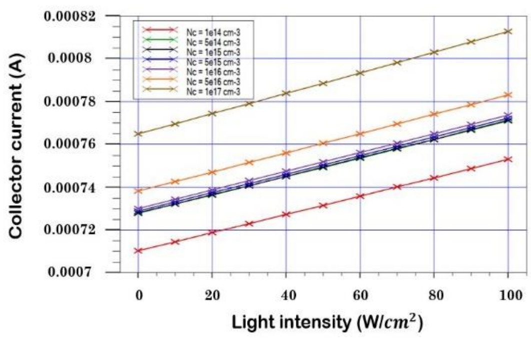

Figure 14. Collector current as a function of light intensity for different collector doping N_c at λ=1550 nm and V_{ce}=1.6 V

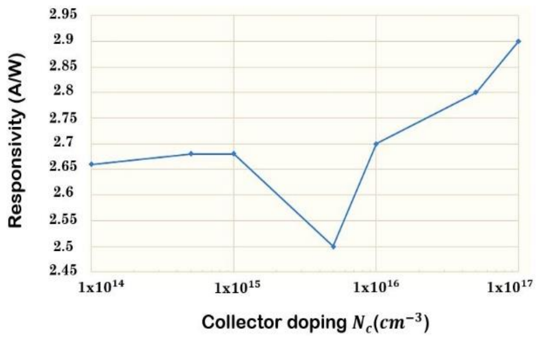

Figure 15. Responsivity as a function of collector doping N_c at λ=1550 nm and V_{ce}=1.6 V

3.1.3. Proposition of optimized structures

Based on the study of the impact of technological parameters on the responsivity of the phototransistor HPT InP/InGaAs. We proposed four new optimized topologies as shown in Table 2. These topologies can be used as photodetectors in optoelectronic applications. The Figures 16-23 present the simulation results of responsivity for the new optimized topologies of the InP/InGaAs HPT for λ=1310 nm and λ=1550 nm.

Table 2. Proposed optimized topologies HPTs

Changed parameters	Studied structure	Optimized structure A	Optimized structure B	Optimized structure C	Optimized structure D
Base width W_b(nm)	65	50	50	50	50
Base doping N_b(cm^{-3})	1.5x10^{19}	1x10^{19}	5x10^{18}	2x10^{18}	1x10^{18}
Collector doping N_c(cm^{-3})	1x10^{16}	1x10^{17}	1x10^{17}	1x10^{17}	1x10^{17}

A. Responsivity of the optimized structure A

Figures 16 and 17 present the evolution of the collector current I_C as a function of the light intensity in phototransistor mode at V_{ce}=1.6 V respectively for λ=1310 nm and λ=1550 nm. The collector current I_C increases with the increasing of the applied light intensity (W/cm^2) which range between 0 to 100 W/cm^2. The responsivity R_{HPT}(A/W) of the optimized structure A is around 7 A/W for λ=1310 nm, and it is around 3.8 A/W for λ=1550 nm.

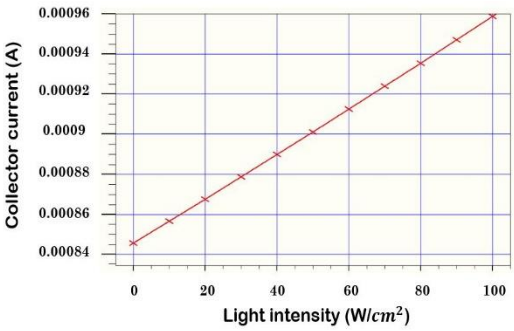

Figure 16. Collector current as a function of light intensity at λ=1310 nm and V_{ce}=1.6 V

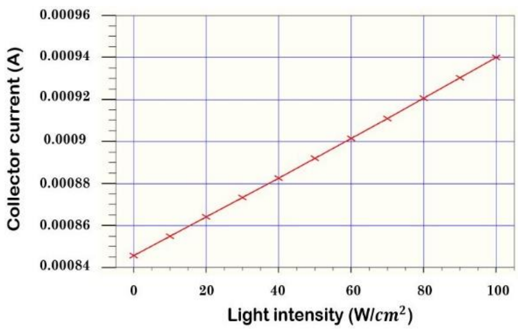

Figure 17. Collector current as a function of light intensity at λ=1550 nm and V_{ce}=1.6 V

B. Responsivity of the optimized structure B

As shown in Figures 18 and 19, the collector current I_C varies as a function of the light intensity in phototransistor mode at V_{ce}=1.6 V respectively for λ=1310 nm and λ=1550 nm. We applied light intensity (W/cm^2) ranging from 0 to 100 W/cm^2. We noticed that the collector current I_C is increasing with the increase of the light intensity (W/cm^2). The responsivity R_{HPT}(A/W) of the optimized structure B is around 13.1 A/W for λ=1310 nm, and it is around 10.9 A/W for λ=1550 nm.

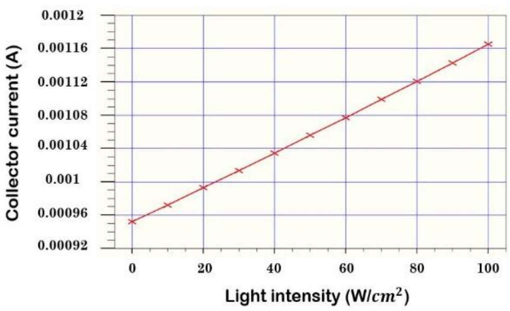

Figure 18. Collector current as a function of light intensity at λ=1310 nm and V_{ce}=1.6 V

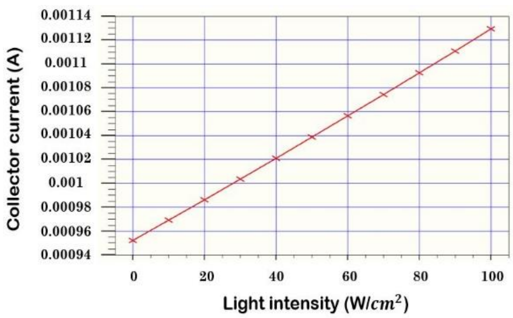

Figure 19. Collector current as a function of light intensity at λ=1550 nm and V_{ce}=1.6 V

C. Responsivity of the optimized structure C

From Figures 20 and 21, the collector current varies according to the light intensity in phototransistor mode at V_{ce}=1.6 V respectively for λ=1310 nm and λ=1550 nm. The collector current increases gradually with increasing application of light intensities ranging from 0 to 100 W/cm^2. The responsivity R_{HPT}(A/W) of the optimized structure C is around 29.3 A/W for λ=1310 nm, and it is around 24.3 A/W for λ=1550 nm.

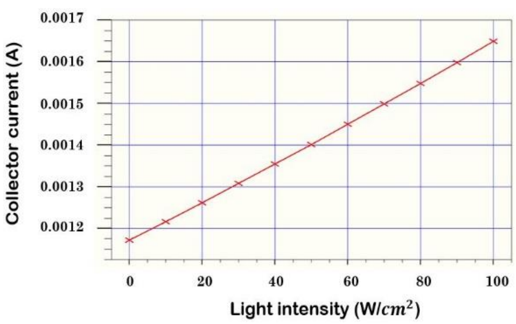

Figure 20. Collector current as a function of light intensity at λ=1310 nm and V_{ce}=1.6 V

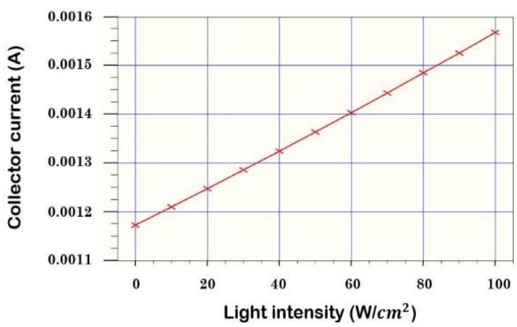

Figure 21. Collector current as a function of light intensity at λ=1550 nm and V_{ce}=1.6 V

D. Responsivity of the optimized structure D

According to Figures 22 and 23, the collector current evolves in a linear way with the application of the light intensity in phototransistor mode at V_{ce}=1.6 V respectively for λ=1310 nm and λ=1550 nm. The light intensity varies from 0 to 100 W/cm^2. The responsivity R_{HPT}(A/W) of the optimized structure D is equal to 57.8 A/W for λ=1310 nm, and it is of the order of 48.1 A/W for λ=1550 nm.

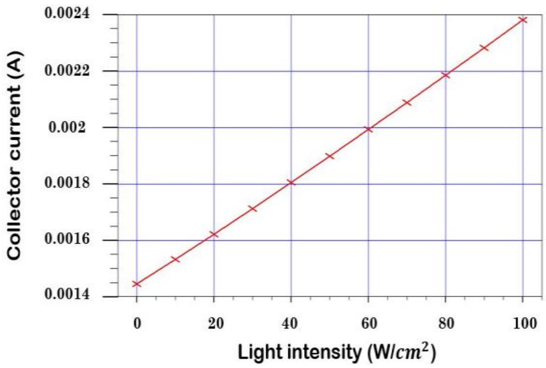

Figure 22. Collector current as a function of light intensity at λ=1310 nm and V_{ce}=1.6 V

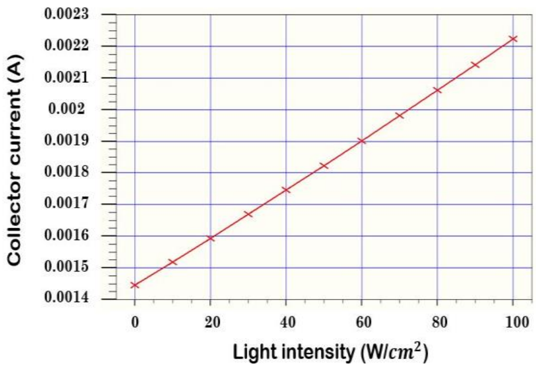

Figure 23. Collector current as a function of light intensity at λ=1550 nm and V_{ce}=1.6 V

3.1.4. Comparison with other research works

Table 3 presents the comparison between our results and some other research works, we were able to design photodetector topologies based on HPT InP/InGaAs. We obtained promising results in terms of responsivity which is a performance parameter allowing the characterization of photodetectors. These optimized structures can be used for digital fiber and microwave telecommunications applications.

Table 3. Comparison with other research results on InP/InGaAs HPTs

Reference	R_{HPT} (λ=1.31 μm)	R_{HPT} (λ=1.55 μm)
Jeong *et al.* [24]	-	5
Our work before optimization	3.2	2.7
Optimized structure A	7	3.8
Optimized structure B	13.1	10.9
Optimized structure C	29.3	24.3
Optimized structure D	57.8	48.1
Ouchrif *et al.* [25]	10	8.4
Khan *et al.* [5]	11	8.7
HPT without optical waveguide [26]	-	4
HPT with integrated optical waveguide [26]	-	29

4. CONCLUSION

In this present work, we investigated the impact of technological parameters on responsivity of InP/InGaAs HPT. Our results are mainly based on this investigation, and our objective is to design optimized structures using technology computer aided-design (TCAD)-Silvaco at the two wavelengths λ=1310 nm and λ=1550 nm. We proposed four structures. The optimized structure A has a responsivity of 7 A/W for λ=1310 nm and 3.8 A/W for λ=1550 nm. The optimized structure B has a responsivity of 13.1 A/W for λ=1310 nm and 10.9 A/W for λ=1550 nm. The optimized structure C has a responsivity of 29.3 A/W for λ=1310 nm and 24.3 A/W for λ=1550 nm. The optimized structure D has a responsivity of 57.8 A/W for λ=1310 nm and 48.1 A/W for λ=1550 nm. The proposed phototransistors were compared with other research works. These optimized structures can be integrated as photodetectors in different optoelectronic applications.

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